

# Rheological behaviour and functionality of inulin-extra virgin olive oil-based mashed potatoes

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**Summary** Developing products having a high nutritional value and good storage stability during freezing is a challenge. Inulin (I) and extra virgin olive oil (EVOO) have interesting functional properties. The effect of the addition of I and EVOO blends at different I:EVOO ratios (0:0, 0:60, 15:45, 30:30, 45:15, 60:0, 30:45 and 45:30) on the rheological, physical, sensory and structural properties of fresh and frozen/thawed mashed potatoes formulated without and with added cryoprotectants was analysed and compared. Addition of I and EVOO (either alone or blended) reduced apparent viscosity and pseudoplasticity producing softer systems, indicating that both ingredients behave as soft fillers. Samples with added I at the higher concentrations ( $\geq 45 \text{ g kg}^{-1}$ ) showed lower flow index and consistency, which is related to formation of smaller I particles; microphotographs indicated that gelling properties of I depended mostly upon processing. Frozen/thawed samples were judged more acceptable and creamier than their fresh counterparts.

**Keywords** Cryoprotectants, extra virgin olive oil, flow behaviour, freezing, inulin, microstructure, potato puree.

## Introduction

Dietary fibres can provide a multitude of functional properties when they are incorporated in food systems. In most cases, inulin (I) addition to different foods has been done to increase fibre ingestion, in amounts that range from 3 to 6 g per portion, or to assure its bifidogenic nature, by adding 3–8 g per portion (Coussément, 1999). I is currently used in food formulations for its technofunctional properties such as fat replacement, bulk agent, water retention, etc. (O'Brien *et al.*, 2003). A fat-like texture can be obtained by increasing the concentration and the average degree of polymerisation of I above a critical value (Kim *et al.*, 2001).

Olive oil is an important component of the diet of the countries surrounding the Mediterranean Sea. Among vegetable oils, extra virgin olive oil (EVOO) has nutritional and sensory characteristics that make it unique (Bendini *et al.*, 2007). On November 2004, the US Federal Drug Administration (FDA) permitted a claim on olive oil labels concerning: 'the benefits on the risk of coronary heart disease of eating about two tablespoons (23 g) of olive oil daily, because of the monounsaturated fat (MUFA) in olive oil' (US FAD,

2004). It is expected that consumers can attain this daily intake from different olive oil-containing foods.

Foods are commonly found as phase-separated systems, and thus present a heterogeneous microstructure. The incompatibility of food macromolecular compounds enables production of new, value-added, formulated foods (Zimeri & Kokini, 2003a). There is little information on the rheological behaviour of I and how it is affected by possible interactions with other ingredients, like different types of hydrocolloids or starch (Zimeri & Kokini, 2003b). Mashed potatoes (MP) behave like a high-volume-fraction dispersion, so that the addition of I (extra dry matter) would be expected to result in a firmer product. Also, there is no information available referring to the effects produced by EVOO incorporation on the physical characteristics of MP. EVOO is a liquid material, and therefore, upon addition of EVOO, the systems would be expected to be softer whatever the concentration used in this study.

This research work was focused on the possibility of optimising mashed potato formulation complying with an improved nutritional value and high consumer acceptance and simultaneously deriving a mechanistic understanding of the systems. The aim of this work was therefore to study the effect of the addition of I/EVOO blends at different I:EVOO ratios on the rheological, physical, sensory and structural properties of fresh and frozen/thawed MP (designated FMP and F/TMP,

respectively) formulated without and with added cryoprotectants (designated MPA and MPB, respectively).

## Materials and methods

### Materials

The potatoes used were tubers (cv Kennebec) from Aguilar de Campoo (Palencia, Spain). I (Orafti®HP, BENEIO-Orafti, Tienen, Belgium) was a 'long-chain' I with a degree of polymerisation,  $DP > 23$  and purity of 99.5% (producer's data). EVOO (Carbonell, Spain) was chosen for addition to MP. Kappa-carrageenan ( $\kappa$ -C) (GENULACTA carrageenan type LP-60) and xanthan gum (XG) (Keltrol F [E]) were donated by Premium Ingredients, S.L. (Girona, Spain). I/EVOO blends were added to the samples at five different I:EVOO ratios ( $15 \text{ g kg}^{-1}$  (I)/ $45 \text{ g kg}^{-1}$  (EVOO), 15:45;  $30 \text{ g kg}^{-1}$  (I)/ $30 \text{ g kg}^{-1}$  (EVOO), 30:30;  $45 \text{ g kg}^{-1}$  (I)/ $15 \text{ g kg}^{-1}$  (EVOO), 45:15;  $30 \text{ g kg}^{-1}$  (I)/ $45 \text{ g kg}^{-1}$  (EVOO), 30:45;  $45 \text{ g kg}^{-1}$  (I)/ $30 \text{ g kg}^{-1}$  (EVOO), 45:30). Samples without added ingredients (0:0 control), with  $60 \text{ g kg}^{-1}$  added I alone (60:0) and with  $60 \text{ g kg}^{-1}$  added EVOO alone (0:60) were also prepared for each type of MP and processing conditions. In this way, the effect of adding ingredients (0:0 vs. 0:60/15:45/30:30/45:15/60:0 or vs. 30:45/45:30), the effect of the variation of I:EVOO ratio at a fixed total concentration (0:60/15:45/30:30/45:15/60:0) and the effect of either adding EVOO at a fixed I concentration (30:30/30:45 or 45:15/45:30) or adding I at a fixed EVOO content (15:45/30:45 or 30:30/45:30) can be analysed.

### Preparation of MP samples

Tubers were manually washed, peeled and diced. MP samples were prepared in  $\sim 2000\text{-g}$  batches from  $607.7 \text{ g kg}^{-1}$  of potatoes,  $230.8 \text{ g kg}^{-1}$  of semi-skimmed in-bottle sterilised milk,  $153.8 \text{ g kg}^{-1}$  of water,  $7.7 \text{ g kg}^{-1}$  of salt (NaCl) and EVOO ( $0\text{--}60 \text{ g kg}^{-1}$ ) using a TM 31 food processor (Vorwerk España, M.S.L., S.C., Madrid, Spain). I ( $0\text{--}60 \text{ g kg}^{-1}$ ) was previously dissolved in  $384.6 \text{ g kg}^{-1}$  of water and milk at  $70^\circ\text{C}$  for 15 min, agitating with a magnetic stirrer at 600 r.p.m. MP were prepared without and with added  $\kappa$ -C and XG (MPA and MPB samples, respectively). In the latter case, hydrocolloids (each at  $1.5 \text{ g kg}^{-1}$ ) were added to the rest of the ingredients in the form of a dry powder. The ingredients were cooked for 35 min at  $90^\circ\text{C}$  (blade speed: 40 r.p.m.) (Alvarez *et al.*, 2008, 2009). The mash was ground for 40 s (blade speed: 1200 r.p.m.) and for 20 s (blade speed: 2600 r.p.m.), and then the product was immediately homogenised through a stainless steel sieve (diameter: 1.5 mm). Half of each fresh blend (FMP samples) was analysed immediately, and the other half was frozen and thawed (F/TMP

samples). Two repetitions of each composition were prepared. Freezing, thawing and heating procedures can be consulted in Supporting information.

### Freezing, thawing and heating procedures

Following preparation, MP samples were placed on flat freezing and microwave thawing trays and then frozen by forced convection with liquid nitrogen vapour in an Instron programmable chamber (model 3119-05,  $-70/+250^\circ\text{C}$ ) at  $-60^\circ\text{C}$  until their thermal centres reached  $-24^\circ\text{C}$  (Fernández *et al.*, 2009) (Supporting information). After freezing, the samples were packed in polyethylene plastic bags, sealed under light vacuum ( $-0.05 \text{ MPa}$ ) on a Multivac packing machine (Sepp Haggenmüller KG, Wolfertschwenden, Germany), and placed in a domestic freezer for storage at  $-24^\circ\text{C}$ . Packed frozen samples were thawed in a Samsung M1712N microwave oven (Samsung Electronics S.A., Madrid, Spain). Samples were heated for 20 min at an output power rating of 600 W. After thawing, the temperature reached at the product thermal centre was measured in all cases ( $+50 \pm 5^\circ\text{C}$ ). Samples were brought up to  $55^\circ\text{C}$  by placing them in a Hetofrig CB60VS water bath (Heto Lab Equipment A/S, Birkerød, Denmark). Sample testing temperature was  $55^\circ\text{C}$  as this is the preferred temperature for consumption of MP (Alvarez *et al.*, 2008, 2009).

### Rheological measurements

A Bohlin CVR 50 controlled stress rheometer (Bohlin Instruments Ltd., Cirencester, UK) was used to conduct steady shear experiments using parallel plate geometry (40 mm diameter; 2 mm gap) and a solvent trap to minimise moisture loss during tests. After loading the sample, a waiting period of 5 min was used to allow the sample to recover and to reach  $55^\circ\text{C}$ . Sample temperature was kept constant during measurements by means of a Peltier plate system ( $-40$  to  $+180^\circ\text{C}$ ; Bohlin Instruments). Sample flow was measured by recording shear stress ( $\sigma$ ) values when shearing with an increasing shear rate ( $\dot{\gamma}$ ) from  $0.1$  to  $120 \text{ s}^{-1}$  for a period of 15 min, which is the range of interest in food texture studies (Bistany & Kokini, 1983). Viscosity values in the upward viscosity/shear rate curves at a shear rate of  $50 \text{ s}^{-1}$  ( $\eta_{\text{app},50}$ , Pa s) were taken as the apparent viscosities of the samples. Experimental data were fitted to the Ostwald de Waele and Casson models using shear stress data obtained from increasing shear rate measurements (Fernández *et al.*, 2008). The flow behaviour index ( $n$ ) and the consistency index ( $K$ ,  $\text{Pa s}^n$ ) were obtained from the de Waele model and the Casson yield stress ( $\sigma_{0C}$ , Pa) and the Casson plastic viscosity ( $\eta_C$ , Pa s) from the Casson model.

## Other quality parameters

The colour of the MP samples in the pots was measured using a HunterLab model D25 (Reston, VA, USA) colour difference metre fitted with a 5-cm-diameter aperture. Results were expressed in accordance with the CIELAB system with reference to illuminant D65 and a visual angle of 10°. A yellowness index (YI) was calculated as  $142.86b^*/L^*$  (Fernández *et al.*, 2008), where  $L^*$  is the lightness of the colour and  $b^*$  its position between yellow and blue. Total soluble solids (TSS) content  $\text{g } 100 \text{ g}^{-1}$  (w/w) as measured by refractive index was determined with an Atago (Itabashi-ku, Tokyo, Japan) dbx-30 refractometer. Expressible water ( $E_w$ ) was measured by centrifugal force according to Eliasson & Kim (1992).  $E_w$  was expressed as the percentage of liquid separated per total weight of sample in the centrifuge tube. Measurements were performed in quadruplicate and the results averaged.

## Sensory analysis

Sensory assessment was conducted by a fourteen-member untrained panel. MP samples were subjected to an overall acceptability (OA) test based on all sensory attributes (texture, colour, taste), on a 9-point hedonic scale (1 = dislike extremely and 9 = like extremely).

## Scanning electron microscopy (SEM)

MP microstructure was examined by SEM using a Hitachi model S-2.100 microscope (CENIM-CSIC). MP samples were air-dried, then mounted and sputter-coated with Au (200 Å approx.) in a SPI diode sputtering system metalliser. Photomicrographs were taken with a digital system Scanvision 1.2 of RONTec (800 × 1.200 pixel).

## Statistical analysis

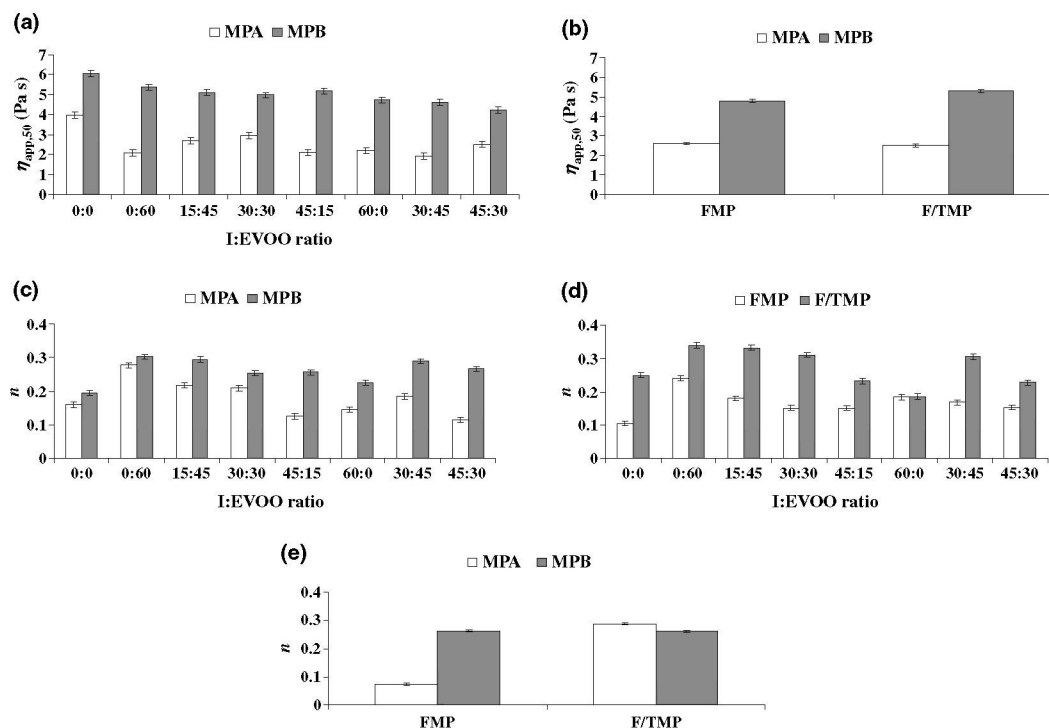
A three-way ANOVA with interactions was applied to evaluate how (I + EVOO) blend, presence or absence of hydrocolloids and performance or not of freezing and thawing affected the rheological properties, YI index, TSS content and the OA of the MP.  $E_w$  was zero for all MPB samples; in this case, a two-way ANOVA with interactions was applied to evaluate how (I + EVOO) blend and processing affected the water-holding capacity (WHC) of the products. Minimum significant differences were calculated using Fisher's least significant difference tests with a 99% confidence interval for the comparison of instrumental parameters, and a 95% confidence interval for comparison of OA. Statistical analyses were performed with STATGRAPHICS® software version 5.0 (STSC Inc., Rockville, MD, USA).

## Results and discussion

### Influence of composition and processing on steady shear measurements of MP samples

Effects of I:EVOO ratio, cryoprotectant addition and processing on the values of the rheological properties derived from flow curves are shown in Table S1. The three binary interactions between factors had a significant effect on the  $\eta$ ,  $K$ ,  $\sigma_{0C}$  and  $\eta_C$  values, meaning that the effect of the I:EVOO ratio on the rheological properties was dependent on the presence of cryoprotectants and processing. Also, interactions between the I:EVOO ratio and cryoprotectant addition, and between this and processing significantly affected the  $\eta_{app,50}$  value. Graphs of the rheological properties with different binary interactions are shown in Figs 1 and 2. The graph of variation in the  $\eta_{app,50}$  value based on the I:EVOO ratio for both MPA and MPB samples (Fig. 1a) shows that, in all cases,  $\eta_{app,50}$  was lower in the MPA than in the MPB samples. Therefore, the latter samples were thicker because of the presence of  $\kappa$ -C in the systems, which caused an increase in starch-alone viscosity, confirming previous findings (Fernández *et al.*, 2009). All the other samples (both MPA and MPB) had significantly lower  $\eta_{app,50}$  values than the 0:0 control. As a result, addition of I and/or EVOO (either alone or blended) produced softer, liquid-like systems.

In the MPB products, the lowest  $\eta_{app,50}$  value with respect to 0:0 control was recorded at a ratio of 45:30, indicating that in these systems with higher total I/EVOO content, adding I caused more softening than adding EVOO (30:45 vs. 45:30). Also, at a fixed total concentration ( $60 \text{ g kg}^{-1}$ ), the viscosity values were higher at a ratio of 0:60 and lower at a ratio of 60:0. In the MPA samples with added I/EVOO at a ratio of 30:30, there was positive synergism effect between I and EVOO in their effect on the  $\eta_{app,50}$  value when compared to the values obtained when they were added singly (ratios of 0:60 and 60:0). At a fixed EVOO concentration, in both MPA and MPB samples, the  $\eta_{app,50}$  values decreased with increasing I concentration. At a fixed I concentration, again in both MPA and MPB samples, the  $\eta_{app,50}$  values decreased with increasing EVOO concentration from 30 to 45  $\text{g kg}^{-1}$ , although at the highest fixed I content, a significant increase in the MPA sample viscosity was detected with increasing EVOO concentration from 15 to 30  $\text{g kg}^{-1}$ . These results suggest that I was a more significant factor in the decrease in apparent viscosity of the systems than EVOO. The processing-dependent variation in  $\eta_{app,50}$  value for MPA and MPB samples is shown in Fig. 1b. Processing did not significantly affect sample viscosity in the MPA samples but significantly increased it in MPB ones. This behaviour reflects the fact that much stronger and more cohesive networks are formed when solutions



**Figure 1** Rheological properties of MP samples: (a), (b) apparent viscosity; (c), (d), (e) flow behaviour index.

of XG are frozen/thawed (Giannouli & Morris, 2003). XG effect may be explained by amylose/XG interactions, which compete against amylose/amylose interactions, retarding or avoiding retrogradation and softening.

The  $n$  index, which indicates the extent of shear-thinning behaviour as it deviates from 1, was also higher in the MPB than in the MPA samples (Fig. 1c). This result might appear contradictory because firmer systems (higher  $\eta_{app,50}$  values, Fig. 1a) would be expected to have lower  $n$  values. However, the probable explanation lies in the XG–water interactions that take place in systems containing cryoprotectants (Alvarez *et al.*, 2008, 2009). MPB samples occlude a great amount of water, which results in less shear thinning (higher  $n$  index). In the latter systems again, all the other samples had significantly higher values of  $n$  with respect to 0:0 control, indicating that the addition of both I and EVOO (either alone or combined) reduced pseudoplasticity. MPB samples with higher EVOO concentrations (ratios 0:60, 15:45 and 30:45) had higher flow index values, which is clearly related to the increase in the oil-phase volume fraction. Further, in samples containing cryoprotectants with fixed I or EVOO concentrations, only an increase in the EVOO concentration from 30 to 45 g kg<sup>-1</sup> produced a significant increase in the  $n$  value. The range of variation in pseudoplasticity was greater in

the flow of the MPA (0.02–0.40) than the MPB (0.17–0.29) samples. Therefore, the I:EVOO ratio had a less significant effect on flow behaviour in the MPB systems, corroborating the ability of  $\kappa$ -C and XG to provide freeze/thaw stability (Alvarez *et al.*, 2009). In the MPA systems, only samples with ingredients added at ratios of 45:15 and 45:30 had significantly higher pseudoplasticity than 0:0 control. The increase in pseudoplasticity of the MPA samples formulated with I/EVOO blends at the highest I concentration may be attributed to the exclusion effect of the starch, which leads to the formation of aggregates containing I crystals. These aggregates retain a large amount of liquid phase and increase the volume fraction (Bot *et al.*, 2004). In the MPB samples, at a fixed total concentration, the  $n$  value significantly increased with increasing EVOO and decreasing I contents, whereas at a fixed EVOO concentration, pseudoplasticity significantly increased with increasing I content (15:45 vs. 30:45 and 30:30 vs. 45:30).

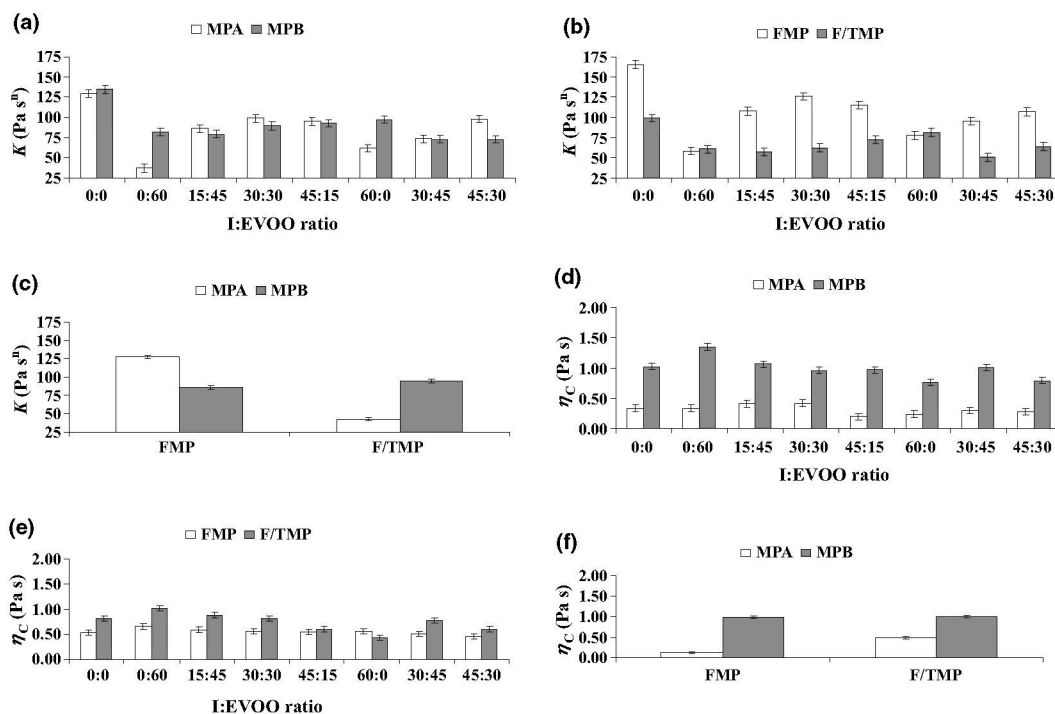
Except at a ratio of 60:0, FMP samples showed significantly lower  $n$  values than their F/TMP counterparts (Fig. 1d), which could be ascribed to phase separation caused by retrogradation of the starch occurring in the processed MPA systems (Eliasson & Kim, 1992). In the F/TMP products, the variation of the I:EVOO ratio at a fixed total concentration showed that

when EVOO increased and I decreased (0:60, 15:45 and 30:30 ratios), the products behaved like more liquid systems. On the contrary, the addition of the highest I concentration (60:0 ratio) significantly increased pseudoplasticity when compared to 0:0 control. Also, at a fixed EVOO content, pseudoplasticity increased linearly with I content (15:45 vs. 30:45 ratio and 30:30 vs. 45:30 ratio). This result is likely related to the formation of small insoluble I particles. Such small particles can be produced by controlling heating and cooling of the dissolved I to induce nucleation and thus small insoluble crystal formation (Hébert *et al.*, 1998). Franck and De Leenheer (2005) reported that at a high concentration ( $>15\%$  for long-chain I), I forms a network composed of solid crystalline particles after shearing, which confers gel-like texture to it. Flow index seems to indicate that, in the F/TMP systems, the presence of I at quite high concentration ( $\geq 45 \text{ g kg}^{-1}$ ) favoured the development and manifestation of its gelling properties.

In the FMP systems, all samples with added ingredients had significantly higher  $n$  values than 0:0 control, although the decrease in pseudoplasticity was greater in the flow of the samples with cryoprotectants added at 0:60. This result indicates greater loss of firmness in the product with the highest EVOO content. However, in the fresh systems, the effect of either adding EVOO at a fixed I concentration or adding I at a fixed EVOO

concentration was nonsignificant. Moreover, for the MPB samples, processing did not significantly affect the sample flow index, whereas there was a considerable increase in the MPA samples (Fig. 1e). It may be that the amorphous matrix formed by  $\kappa$ -C, XG and starch granules stabilise the I crystals by reducing the contact between I chains and consequently their rate of aggregation.

Variations in the  $K$  values of I:EVOO ratios in both MPA and MPB samples (Fig. 2a) and both FMP and F/TMP samples were quite similar to those observed in the  $n$  values (Fig. 2b) – i.e. addition of I/EVOO blends increased the value of  $n$  and reduced the  $K$  value. In both MPA and FMP products, the decrease in consistency with respect to 0:0 ratio sample was generally greater when either I or EVOO was added alone, suggesting a possible synergistic effect between the two ingredients. There were nonsignificant differences in the  $K$  values of the MPA samples with added 30:30 and 45:15 ratios (Fig. 2a), indicating that  $15 \text{ g kg}^{-1}$  of both ingredients at a fixed concentration produce a similar effect on the potato matrix. Also, at a fixed I concentration, MPA sample consistency decreased with EVOO content (30:30 vs. 30:45). In the FMP samples (Fig. 2b), at fixed EVOO and I contents, the  $K$  value decreased linearly with increasing I or EVOO contents, respectively. In the MPB samples, at a fixed total concentration, the samples with higher EVOO content (ratios 0:60 and



**Figure 2** Rheological properties of MP samples: (a), (b), (c) consistency index; (d), (e), (f) Casson plastic viscosity.

15:45) presented lower consistency values, although these values were more or less similar to the values of the samples with higher total added concentration (30:45 and 45:30). Also, in the F/TMP samples, the effect of increasing EVOO content at a fixed I concentration was more significant than the effect of increasing I content at a fixed EVOO concentration (Fig. 2b). Processing significantly reduced the consistency of the samples without added cryoprotectants (MPA) but increased slightly in the case of the samples with added cryoprotectants (MPB) (Fig. 2c). In the latter systems, contact between I chains becomes easier during cooling, promoting the formation of aggregates of small I crystals (Villegas *et al.*, 2007).

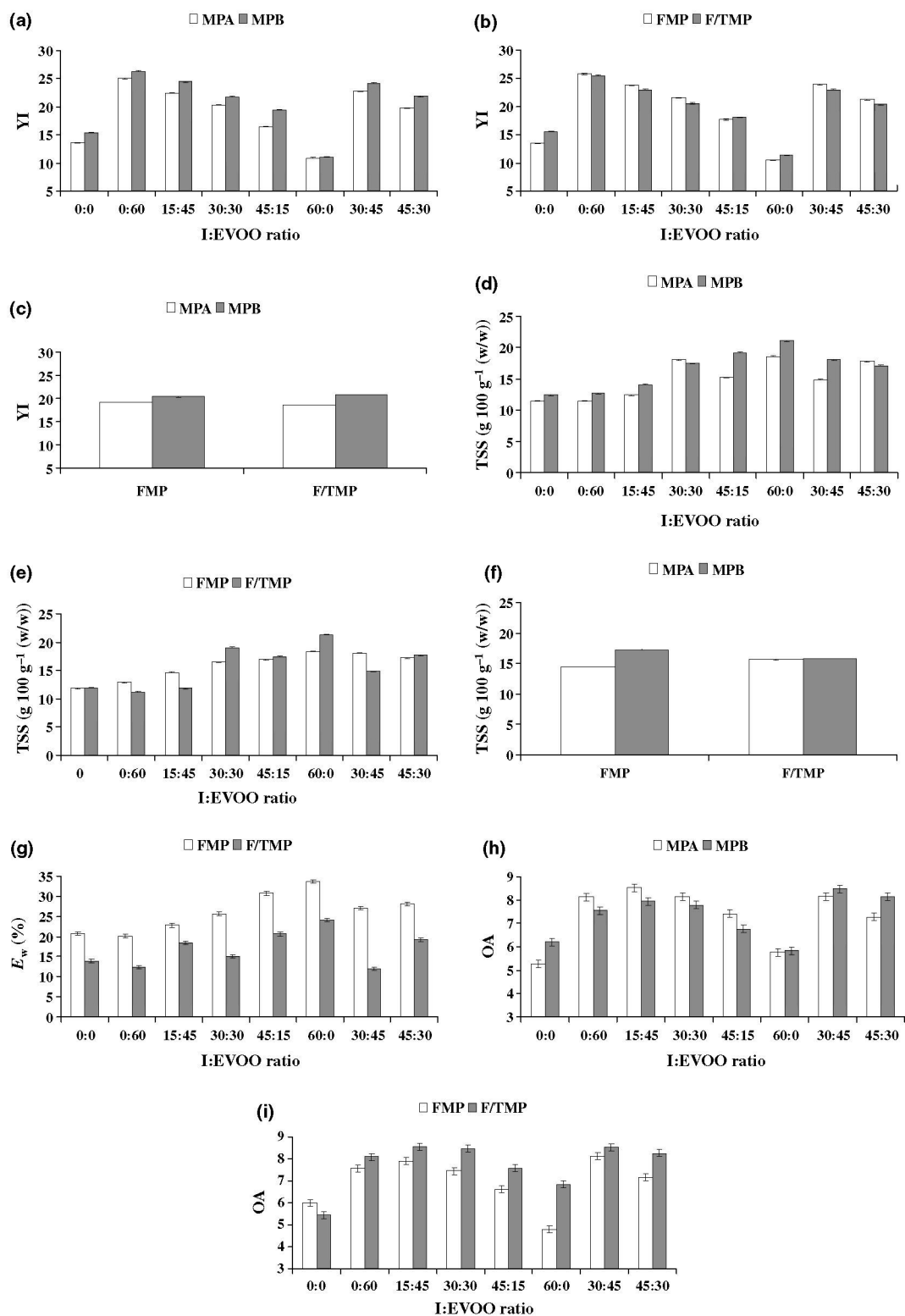
The variation in the  $\sigma_{0C}$  values with the I:EVOO ratio was very similar to that observed in the values of  $K$  (Table S1), and therefore graphs have been omitted. In all cases,  $\eta_C$  values were greater in the MPB than in the MPA samples (Fig. 2d). This result is related to the absolute WHC of the samples containing XG, and therefore to water plasticiser action (Fernández *et al.*, 2008, 2009). In the MPB products, at a fixed total concentration samples with added 0:60 ratio had significantly higher  $\eta_C$  values than the rest, whereas samples with added 60:0 ratio had lower  $\eta_C$  values than the 0:0 control. However, there were nonsignificant differences between the plastic viscosity of the samples with added cryoprotectants at ratios of 15:45, 30:30, 45:15 and the control. Also, the  $\eta_C$  value in MPB samples with a ratio of 30:45 addition was similar to that of the control without added ingredients. One possible mechanism by which the oil increased the  $\eta_C$  value is through lubrication and coating properties (de Wijk *et al.*, 2003). In MPA products, there were nonsignificant differences between the  $\eta_C$  values of the samples with 45:15, 60:0, 30:45 and 45:30 added cryoprotectants, all of them with high I content ( $\geq 30$  g kg<sup>-1</sup>). The  $\eta_C$  value was almost constant in the FMP samples (Fig. 2e), whereas in the F/TMP samples, Casson plastic viscosity was again lower in the ones with I added alone (ratio 60:0); in the case of the samples with added I/EVOO blends, the ones with higher I content (ratios 45:15 and 45:30) had significantly lower  $\eta_C$  values than the 0:0 control. EVOO content would moreover seem to affect the plastic viscosity of the samples more than I. Processing significantly increased  $\eta_C$  in the MPA samples but did not significantly affect it in the MPB samples (Fig. 2g), again confirming the freeze-thaw stability conferred by the  $\kappa$ -C/XG blend. There are a number of hypotheses that could explain the decrease of plastic viscosity caused by I incorporation, especially when added at a ratio of 60:0. According to Zimeri & Kokini (2003a), this fact could be related to inulin's structure corresponding to one with no entanglements at all, with agglomerates (crystals) sliding one on top of the other. These authors also indicated that rheological properties

of mixed I-waxy maize starch (WMS) systems at I to WMS ratios of 50:50 presented a decrease in the moduli's magnitude because of WMS network disruption by I when compared to gels with lower I concentrations. This mechanism could account for the observed decrease in sample plastic viscosity at the highest I content. In addition, at an I to EVOO ratio of 60:0, potato starch and I probably gelled independently, with potato starch remaining in the amorphous state (Zimeri & Kokini, 2003b) and I recrystallising (Zimeri & Kokini, 2002).

#### **Influence of composition and processing on colour, total soluble solids content, $E_w$ and OA of MP samples**

Effects of I:EVOO ratio, cryoprotectant addition and processing on the values of YI, TSS content, expressible water ( $E_w$ ) and overall acceptability (OA) of the MP samples are shown in Table S2. Processing and cryoprotectant addition did not significantly affect the YI index and the OA of the samples, respectively. The three binary interactions had a significant effect on YI index and TSS content of the samples. Also, AC interaction had a significant effect on  $E_w$ , whereas both AB and AC interactions significantly affected the OA scores.

The variation in the YI value based on I:EVOO ratio for both MPA and MPB samples (Fig. 3a) shows that in both cases, the highest and lowest YI values were registered in the samples containing 0:60 and 60:0 ratios, respectively. An increase in EVOO level favours either a higher  $L^*$  value (lightness) because of an increase in the overall light scattering associated with the scattering properties of fat (Chantrapornchai *et al.*, 1999), as well as a higher  $b^*$  value because of an increase in chloroplast pigment (chlorophyll and carotenoids) content. In addition, at a fixed concentration, YI decreased linearly with increasing and decreasing I and EVOO contents, respectively (0:60, 15:45, 30:30, 45:15). Unlike EVOO, I is a white powder and produced a lighter-coloured mashed potato (higher  $L^*/b^*$  ratio). In the case of I/EVOO blends addition, except for the lowest EVOO content (60:0 ratio), all the other samples had significantly higher YI values than the 0:0 control (Fig. 3a), indicating that the darkening produced by EVOO addition is stronger than the lightening caused by I incorporation. With regard to 0:0 control, panellists found that increasing yellowness improved the product colour, as the flesh of Kennebec is too white. In turn, lack of colour in samples with added 60:0 ratio could be easily solved by addition of some  $\beta$ -carotene. Also, except for the latter samples, MPB samples had higher YI values than MPA samples. A previous study showed that YI was increased by adding either  $\kappa$ -C or XG alone, and the biopolymer concentration effect was more significant in the processed samples than in the fresh ones (Fernández *et al.*, 2008). In any case, colour



**Figure 3** Quality parameters of MP samples: (a), (b), (c) yellowness index; (d), (e), (f) Total soluble solids content; (g)  $E_w$ ; (h), (i) OA.

parameter values of the MP samples with added 60:0 ratio indicate that the effect caused by cryoprotectant addition is weaker than the lightening produced by I incorporation. By comparing both FMP and F/TMP samples (Fig. 3b), it can be observed that at a fixed EVOO content, the increase in I concentration did not significantly affect the colour of the MP samples (15:45 vs. 30:45 and 30:30 vs. 45:30); whereas at a fixed I concentration, addition of EVOO at higher concentrations considerably increased YI (30:30 vs. 30:45 and 45:15 vs. 45:30). Note moreover that the presence of ingredients significantly reduced differences in the YI values among FMP samples and their F/TMP counterparts. Processing slightly increased yellowness in the MPB samples but did not significantly affect it in the case of the MPA samples (Fig. 3c). This is likely related to the WHC of the MPB samples, enhancing the overall light scattering of the MP.

In both MPA and MPB samples, there were nonsignificant differences between the TSS content of the 0:0 control and the samples with added 0:60 ratio (Fig. 3d). On the other hand, the highest TSS value corresponded to the samples with added I alone (60:0 ratio) and were higher in the MPB products, which is logical as two polysaccharides were also added to MP samples in these cases. At a fixed total concentration, the parameter value increased linearly with increasing I content (0:60, 15:45, 30:30 and 45:15), although MPA samples with a 45:15 addition ratio had lower TSS content than those with a 30:30 ratio. Supplementation with I introduced more reducing sugars and led to increased total carbohydrate content (Cardarelli *et al.*, 2008). Similar results were observed by Castro *et al.* (2009) and Villegas *et al.* (2010) in dairy drinks with added oligofructose and I, respectively. As expected, TSS content did not show a clear trend of behaviour as a consequence of processing (Fig. 3e); differences may be attributed to low standard deviation of the mean values and therefore are of no practical importance. In both fresh and processed samples with 45 g kg<sup>-1</sup> added EVOO, TSS content increased with increasing I concentration (15:45 vs. 30:45); however, only in the FMP samples with 30 g kg<sup>-1</sup> added EVOO, the TSS content did increase with I concentration (30:30 vs. 45:30), indicating that processing affected the parameter only slightly. After processing, TSS increased slightly in the MPA samples but decreased in their MPB counterparts (Fig. 3f). This is a consequence of the fact that substances dissolved in water gather together with ice crystal growth, which is more rapid in absence of cryoprotectants.

The variation in the  $E_w$  value based on the I:EVOO ratio for both FMP and F/TMP samples is shown in Fig. 3g. In both FMP and F/TMP samples and at a fixed total concentration, the lowest and highest  $E_w$  values were registered in samples with added 0:60 and 60:0 ratios, respectively. Also, in the FMP products, the

WHC decreased linearly with increasing I content (0:60, 15:45, 30:30 and 45:15 ratios), indicating that the water present was more 'available' because of weaker water-I interactions. This result is probably because of the presence in the fresh systems of large I particles and reduced density of the same (they entered the solution rather than participating in the water retention). Nevertheless, if we compare 0:0 control and MP samples with added 0:60 ratio, we can see that EVOO by itself did not affect the WHC of MP systems (Table S2). In addition, in all cases, the  $E_w$  percentages were greater in the FMP samples than in the F/TMP ones (Fig. 3g). This fact is partially related to water loss occurring in the processed samples by recrystallisation and sublimation phenomena. However, the results also indicate that the cooling prior to freezing, as well as the freezing process itself, might have favoured conformational changes of the I molecules. This in turn resulted in a smaller solid particle size and a larger surface exposed to interaction with water (Chiavaro *et al.*, 2007), justifying the superior water retention detected in the F/TMP samples. On the other hand, long-chain I particles are held together only by physical interaction between molecules (Ronkart *et al.*, 2010), and possibly the mechanical strength of the crystallised I particles was too little to support the stresses caused by growth of the ice crystals during freezing, and both sedimentation of I crystals as a result of decreasing temperature (Toneli *et al.*, 2008) and subsequent recrystallisation during thawing and heating could have occurred in these systems. After freezing, enough water may be present to allow a small fraction of I to recrystallise with different solubility properties.

The variation in the OA score on the I:EVOO ratio for both MPA and MPB samples and both FMP and F/TMP samples is shown in Fig 3h, i, respectively. The presence of EVOO in the systems significantly increases the acceptability of the products. In both MPA and MPB samples as well as in both FMP and F/TMP samples, at a fixed total concentration, the OA scores were higher when both ingredients were added to the product at a ratio of 15:45. However, there were nonsignificant differences in the OA scores given to the MPB and F/TMP samples at ratios of both 15:45 and 30:30. Samples with 15 g kg<sup>-1</sup> added I and 45 g kg<sup>-1</sup> added EVOO had significantly higher OA scores than those with 60 g kg<sup>-1</sup> added EVOO alone (0:60), indicating a synergistic effect between ingredients, which enhances the consumer acceptance of the product. This result corroborates previous findings, as the properties of I used as a fat substitute are attributed to its capacity to create a fine and creamy texture that provides a mouth sensation similar to that of fat (Bot *et al.*, 2004; Chiavaro *et al.*, 2007). On the other hand, the positive effect of EVOO on the acceptability of the MP samples was ascribed by the panellists chiefly to lubricating and



coating properties conferred by the oil. Fat is a well-known enhancer of creaminess sensations (de Wijk *et al.*, 2003), which covers oral tissue with a coating thereby reducing the friction between food and oral tissue. This may also explain the softening detected in MP samples formulated with EVOO either alone or blended with I. Panellists ascribed other differences between samples to an aromatic and a creamy note detected in the oil-added MP. Also, at a fixed total content, the OA scores were mostly higher in the MPA samples (Fig. 3h), which was attributed to an excessive thickening perceived in the samples containing cryoprotectants (Alvarez *et al.*, 2009).

Other comparisons show that in both MPA and MPB samples with added I/EVOO blends at a fixed concentration (Fig. 3h), the OA score decreased with increasing I content (ratios 15:45, 30:30 and 45:15). However, in the MPB samples and at fixed EVOO or I contents, the OA increased when either the I (15:45 vs. 30:45 and 30:30 vs. 45:30) or the EVOO contents (30:30 vs. 30:45 and 45:15 vs. 45:30) were increased. In the latter systems, both I and EVOO at higher concentrations counteracted the recognised thickening effect produced in these systems by the gelling properties of the  $\kappa$ -C. Generally speaking, in MPB samples, the highest OA score was awarded to the samples with added 30:45 ratio.

Interestingly, at a fixed total ingredients content, all the F/TMP samples were judged more acceptable than their FMP counterparts (Fig. 3i). This result is remarkable because MP samples as formulated here are intended to be frozen and thawed. Panellists judged the FMP products with cryoprotectants added at a ratio of 60:0 as the worst of all, although the OA score of their F/TMP counterparts also increased significantly. Indeed, panellists found that the fresh samples with an added ratio of 60:0 had a sandy texture associated with the presence of large I crystals, which were even visible to the naked eye. Initial I concentration may affect both the crystallisation and the aggregation processes and consequently the rate of sedimentation (Bot *et al.*, 2004). At 60 g kg<sup>-1</sup> I concentration, the chains will crystallise more rapidly, which could explain the sedimentation detected in these samples. Nevertheless, after freezing, imperceptible smaller I particles increased the perception of creaminess as reflected by the higher OA scores received by the F/TMP samples at a ratio of 60:0 (Fig. 3i). This result is also related to an increase in the water–I particle interactions (Kim *et al.*, 2001; Villegas *et al.*, 2007). In general, in the F/TMP systems, the presence of XG probably produced a decrease in water–I particle interactions. Changes in the I moisture content would affect its crystallisation behaviour, and some physical changes like agglomeration or caking could have occurred (Ronkart *et al.*, 2010). The fact is that F/TMP samples with 15:45, 30:30 and 30:45 added

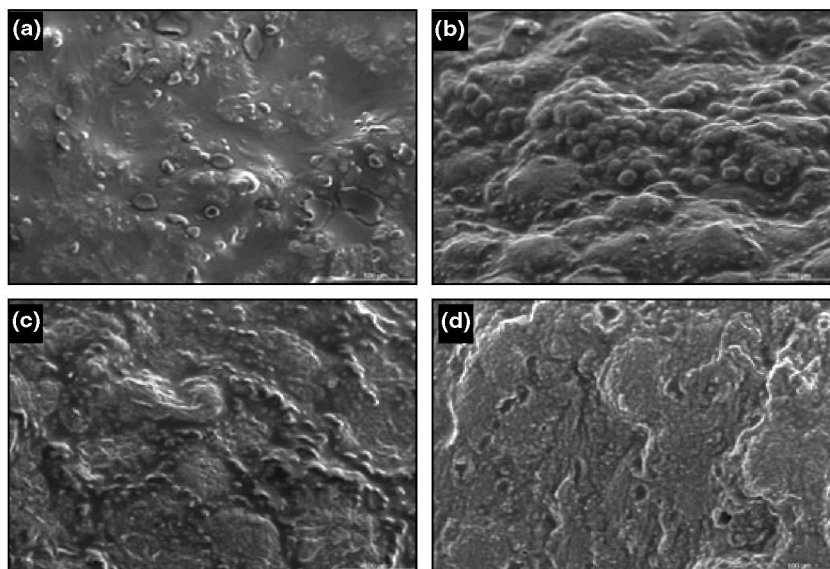
cryoprotectants were equally and significantly preferred by the panellists.

### Microstructure examination

Figure S1a, b show microphotographs of fresh 0:0 control without and with added cryoprotectants, respectively. FMP samples consist mainly of whole single potato cells as well as some ruptured cells and cell fragments that are embedded in an extracellular starch phase blended with gelled  $\kappa$ -C and XG in the case of the MPB samples (Fig. S1b). Figure S1c, d indicate that when the controls were frozen, the tissue was damaged and most of the cells are visibly shrunken. Figure S1d shows the presence of fibres or strands. According to Giannouli and Morris (2003), during freezing, XG chains are forced to align and associate by conversion of water to ice crystals. The forced associations survive upon thawing to give a cryogel network. It is likely that such strands are related to this XG conformational transition.

The microphotograph of the fresh sample without added cryoprotectants and with a ratio of 30:45 (Fig. 4a) shows a dispersed thin phase or layer of oil enveloping all the microstructures constituting the mash. EVOO acts as a soft filler suspended in a rigid matrix. In the fresh sample with both cryoprotectants added at a ratio of 30:30, it is possible to distinguish whole potato cells that are embedded in a continuous network of amylose and  $\kappa$ -C in which starch granules are entrapped. The surface of the cells is relatively smooth, indicating lubricant and coating properties conferred by EVOO. Even though it is not easy to differentiate I from potato starch granules, Fig. 4b shows the presence of some large spherical and obloid-shaped I crystallites embedded in the amorphous and rigid matrix. According to Zimeri & Kokini (2002), these remaining crystals could have been the result of either insolubility or recrystallisation after hot MP samples were cooled to 55 °C for testing. These findings are consistent with other results, as large particles were observed on nonmicrofluidised I dispersions whatever the concentration used (Ronkart *et al.*, 2010). Zimeri & Kokini (2003a), using light microscopy, observed the presence of some I crystals immersed in the continuous phase in water solutions of 5% (w/w) long-chain I.

Both processed counterparts (Fig. 4c, d) show an I-rich phase with smaller I crystallites forming a continuous network. These crystallites are more easily distinguished when the EVOO content is lower (Fig. 4d), and the tissue shows a microstructure formed by clusters of small I crystals. Consequently, freezing caused a reduction in the solid I crystal size which in turn resulted in a softer product with a smoother texture as the reduction in the crystal size correlated with the development of better gelling properties of the I. This



**Figure 4** Microphotographs of MP samples: (a) fresh sample without added cryoprotectants and with added cryoprotectants at a ratio of 30:45; (b) fresh sample without added cryoprotectants and with added cryoprotectants at a ratio of 30:30; (c) processed sample without added cryoprotectants and with added cryoprotectants at a ratio of 30:45; (d) processed sample with added cryoprotectants and with added cryoprotectants at a ratio of 30:30.

reinforced the gelation mechanism of I proposed by Kim *et al.* (2001), Bot *et al.* (2004) and Ronkart *et al.* (2010). Hébert *et al.* (1998) studied the melting behaviour of semi-crystalline chicory root I. Large crystallites resulted from primary nucleation at a higher temperature, and smaller crystallites resulted from secondary nucleation at a lower temperature. Therefore, during cooling associated with the freezing process, a secondary nucleation may possibly occur resulting in the formation of smaller I crystallites.

## Conclusions

Differences in the rheological behaviour of MP samples with added I and EVOO blends at I to EVOO ratios of 15:45, 30:30, 45:15, 30:45 and 45:30 were less significant than expected. The I:EVOO ratio mainly affected the colour and the reducing sugars of the products, with I and EVOO producing whiter- and yellower-coloured MP, respectively. Addition of cryoprotectants set the main differences among apparent and plastic viscosities, whereas processing mostly established differences in the flow behaviour, the WHC and the acceptability of the products. In the samples with added I/EVOO blends, the greater the measured  $\eta_{app,50}$  and Casson yield stress, the lower was the OA score; this result indicates that panellists preferred softer systems. Rheological properties confirm that EVOO and I can act as soft fillers, respectively suspended and entrapped in a rigid matrix. I had a more significant effect on the apparent viscosity,

whereas EVOO affected the flow behaviour and consistency indexes more, as well as the plastic viscosity of the systems. In the FMP samples, no signs of I gelling properties was detected, which is ascribed to the large I particle size. On the contrary, development of gelling properties of I-MP systems was observed when the products were frozen and thawed, which is related to the formation of smaller I particles. The addition of I at  $30 \text{ g kg}^{-1}$  and EVOO at  $45 \text{ g kg}^{-1}$  is strongly recommended to achieve an increase in the daily intake of soluble fibre and MUFA with a very similar plastic viscosity to that of conventional MP samples while promoting positive effects on both the colour and the OA of the resulting products. The possibility of slightly increasing the *k*-C concentration (up to  $2 \text{ g kg}^{-1}$ ) in these systems is proposed to counteract the softening caused by both I and EVOO incorporation.

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## Supporting Information

Additional Supporting Information may be found in the online version of this article:

**Figure S1.** Microphotographs of MP samples.

**Table S1.** Effects of I:EVOO ratio, cryoprotectant addition and freezing/thawing on rheological properties of MP samples.

**Table S2.** Effects of I:EVOO ratio, cryoprotectant addition and freezing/thawing on colour, TSS content,  $E_w$  and OA of MP.

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